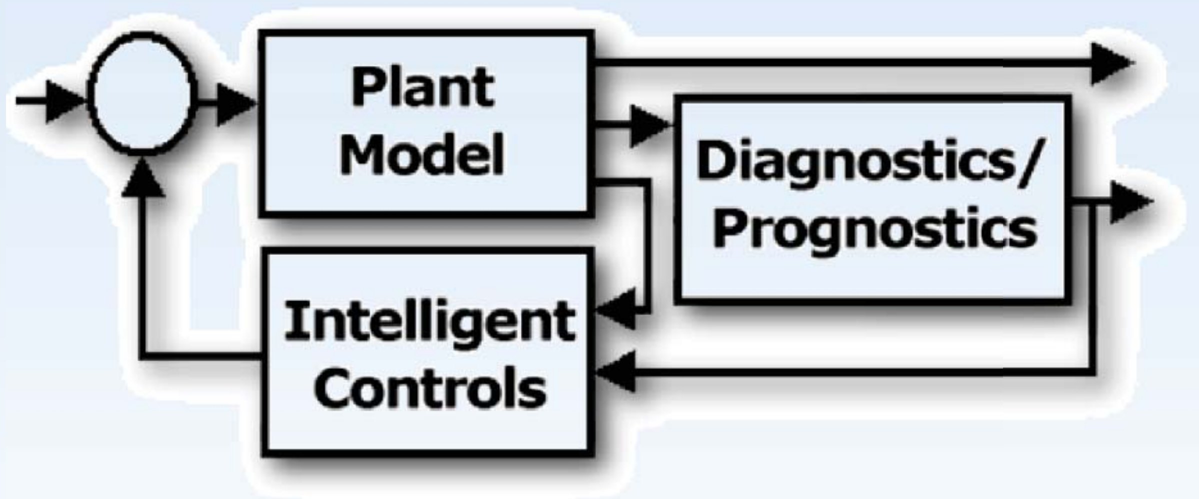
IVHM Related Research at NASA Glenn



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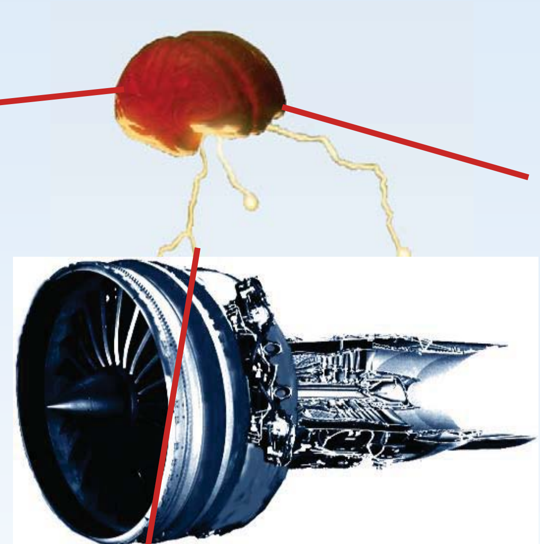
Intelligent Propulsion Systems
Control System perspective

Multifold increase in propulsion system Affordability, Capability Environmental Compatibility, Performance, Reliability and Safety

Active Control Technologies for enhanced performance and reliability, and reduced emissions
- active control of combustor, compressor, vibration etc.
- MEMS based control applications



Advanced Health Management technologies for self diagnostic and prognostic propulsion system
- Life usage monitoring and prediction
- Data fusion from multiple sensors and model based information

Distributed, Fault-Tolerant Engine Control for enhanced reliability, reduced weight and optimal performance with system deterioration
- Smart sensors and actuators
- Robust, adaptive control

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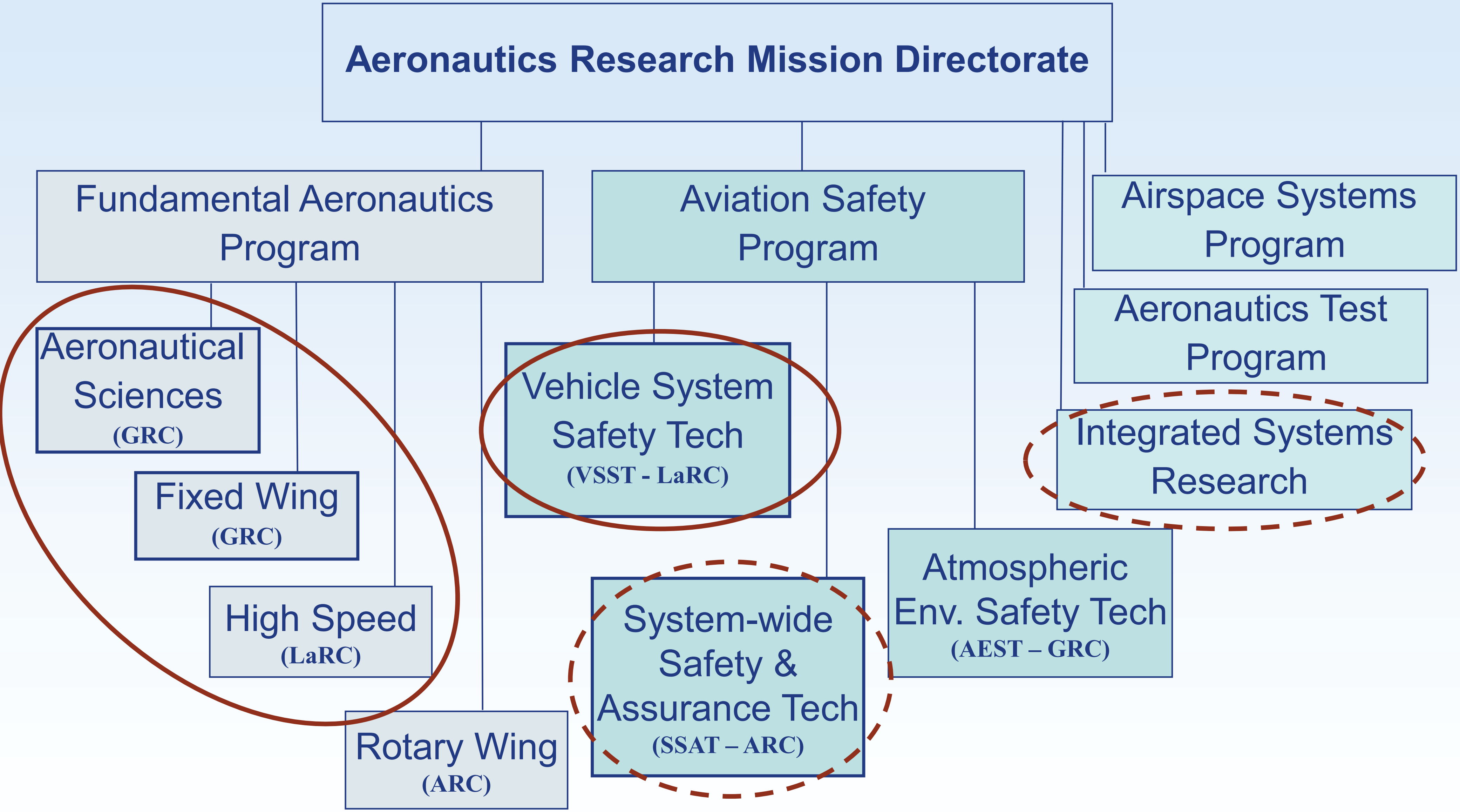
NASA Aeronautics Program Structure
Effective FY13



CDB Tasks Under NASA Aeronautics Research

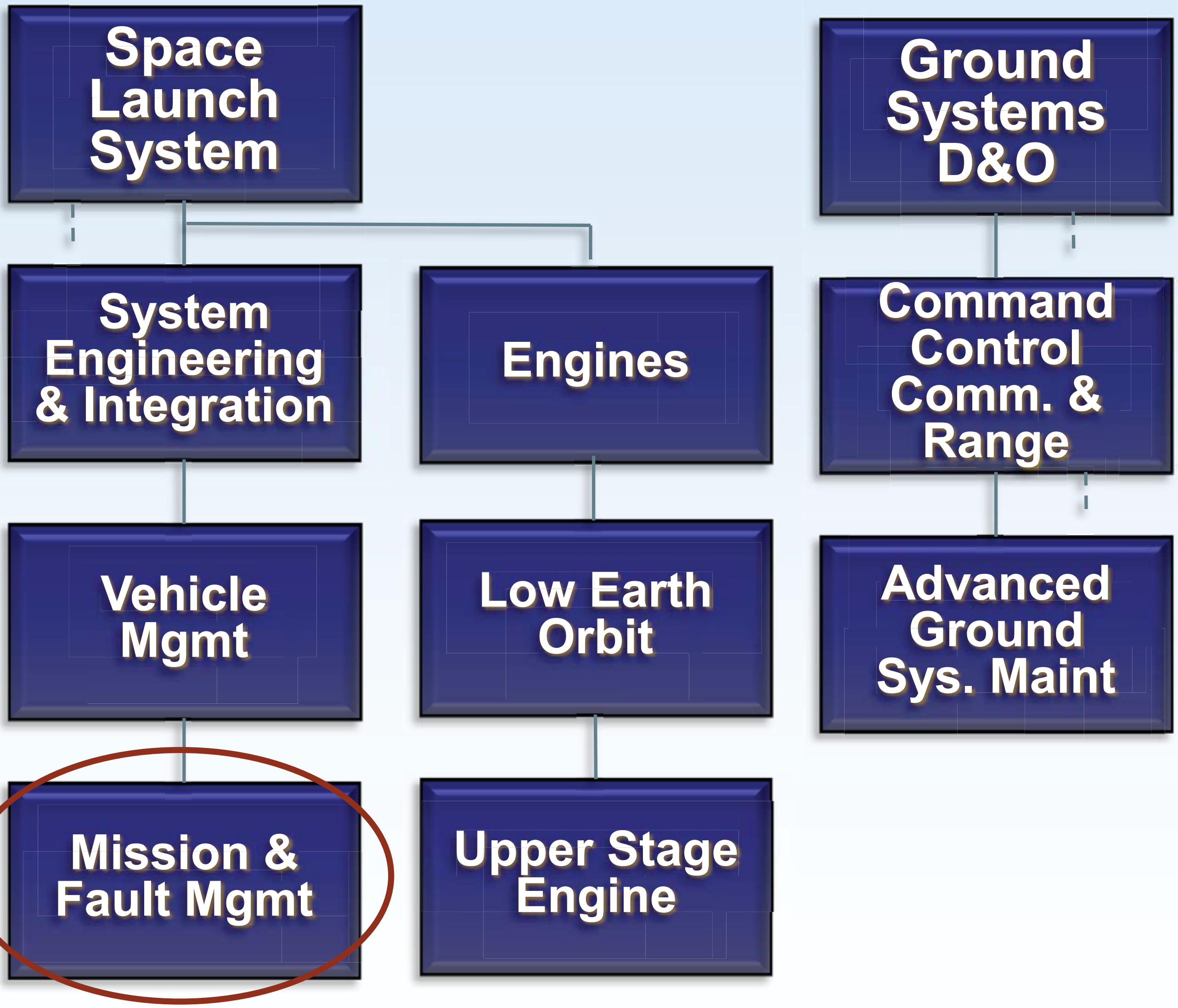
Fundamental Aeronautics Program (FAP)

- Distributed Engine Control – AS
- **Model-Based Engine Control – AS**
- Pressure Gain Combustion – AS
- Dynamic Systems Analysis – FW
- Active Combustion Control – AS
- Aero-Propulso-Servo-Elasticity – HS

Aviation Safety Program

- **Gas Path Health Management – VSST**
- Integrated Resilient Propulsion Control – VSST – complete
- **Robust Propulsion Control – VSST**
- Run-time Validation of Complex Systems - SSAT

Human Exploration and Operations Programs CDB Activities



Autonomous Propulsion System Technology

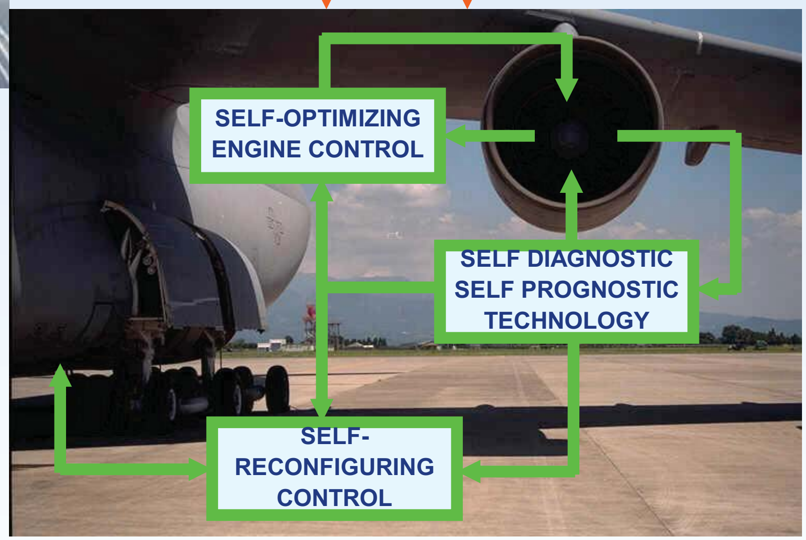
Reduce/Eliminate human dependency in the control and operation of the propulsion system

Demonstrate Technology in a relevant environment

Vehicle Management System

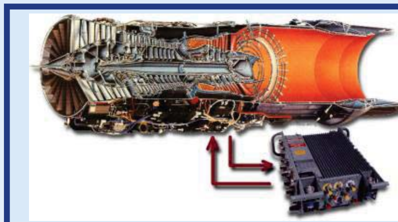
Performance Requirement

Engine Condition/Capability



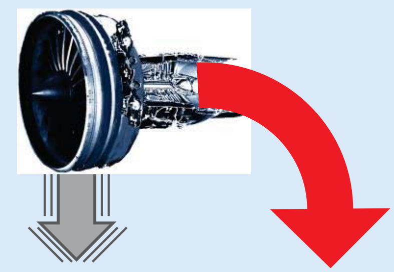
Self-Diagnostic Adaptive Engine Control System

- Performs autonomous propulsion system monitoring, diagnosing, and adapting functions
- Combines information from multiple disparate sources using state-of-the-art data fusion technology
- Communicates with vehicle management system and flight control to optimize overall system performance

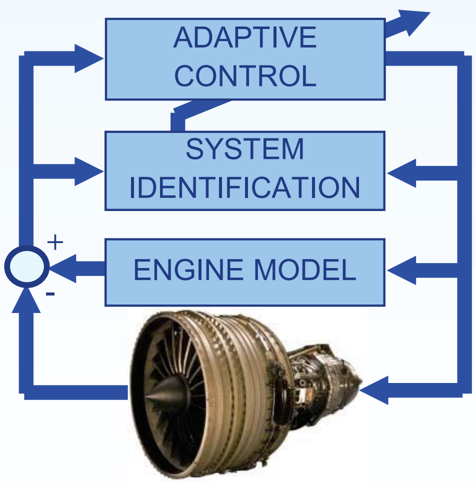


Model-Based Control And Diagnostics

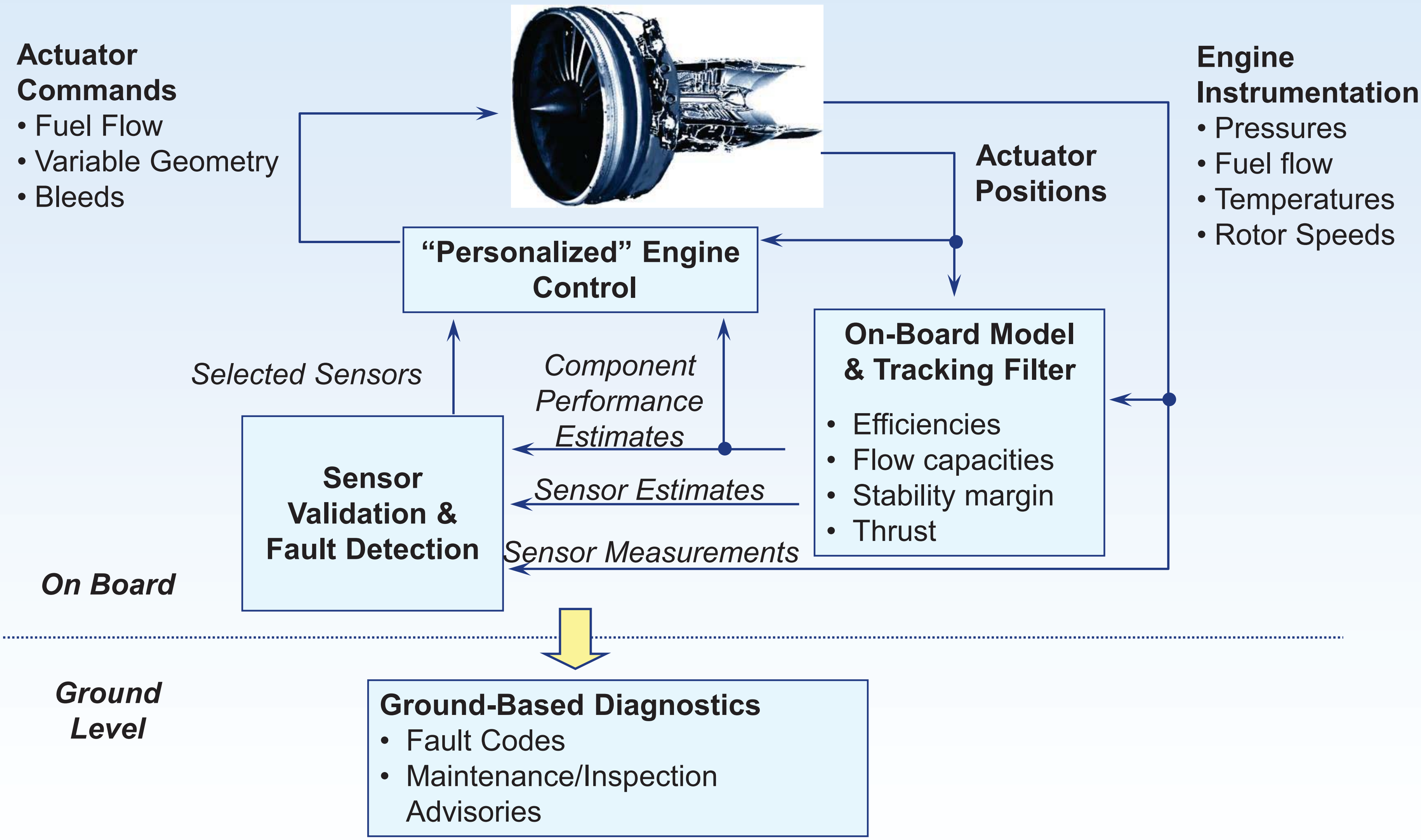
Leverage Technology from other programs



Data Fusion



Model-Based Control and Diagnostics Concept



Optimal Tuner Selection for Kalman Filter-Based Performance Estimation

Background:

- Adaptive on-board engine model
- Applies Kalman filter-based tracking filter

Challenge:

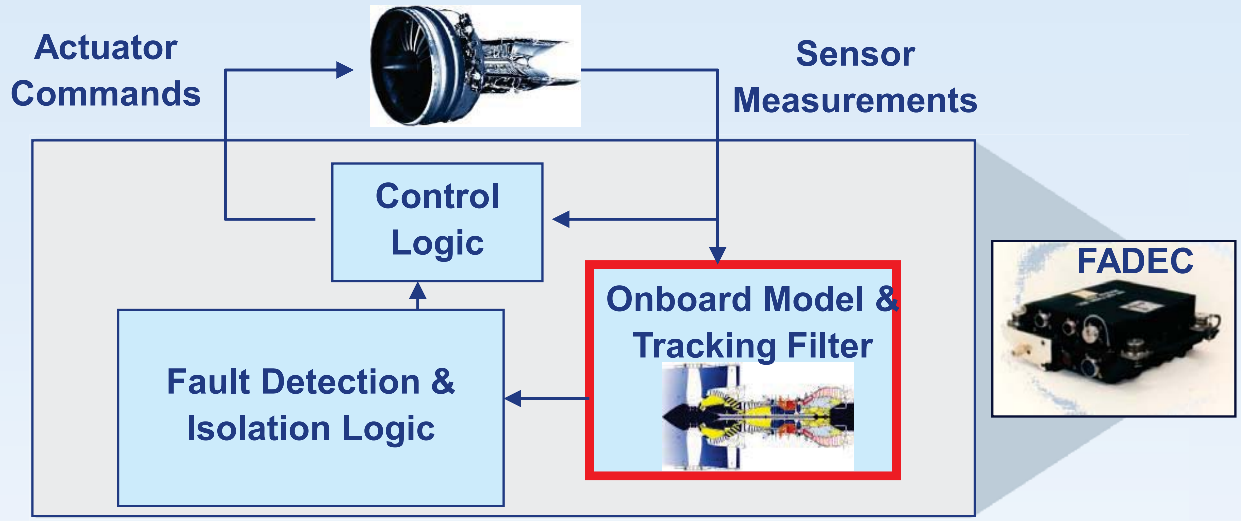
- Underdetermined estimation problem – more unknowns (health parameters) than available sensor measurements

Approach:

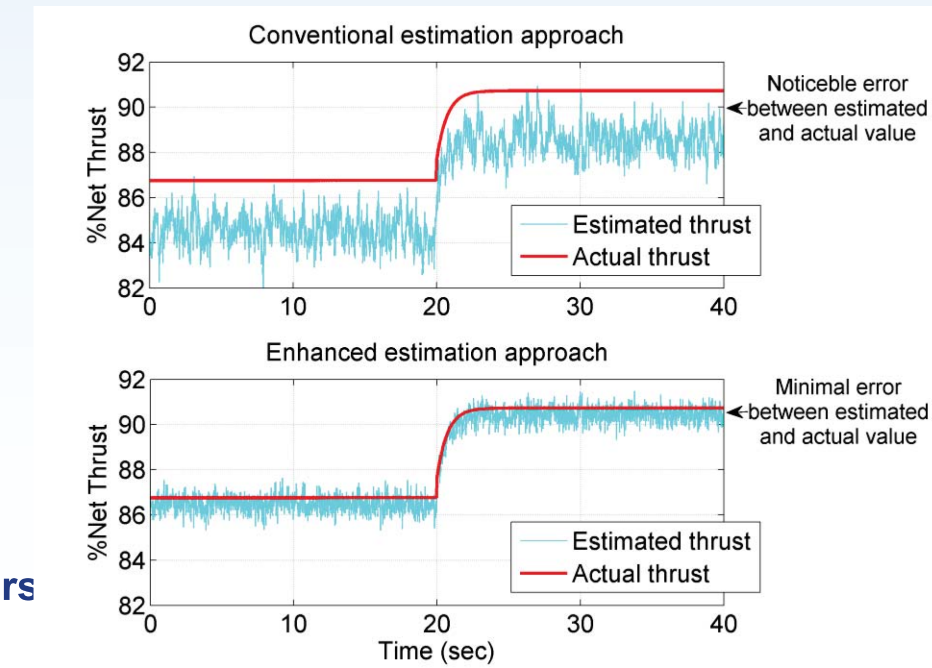
- Define tuner vector that is a linear combination of all health parameters and systematically selected to minimize KF mean squared estimation error in the parameters of interest

Results:

- Linear Monte Carlo simulation studies have shown a mean error reduction of approximately 33%



Model-based Performance Estimation Architecture



Thrust estimation accuracy comparison
(conventional vs. optimal model tuning parameters

An Integrated Architecture for Aircraft Engine Performance Trend Monitoring and Gas Path Fault Diagnostics

Background:

- Conventionally, performance trend monitoring and gas path fault diagnostics are performed off-board, post-flight, based on a limited quantity of "snapshot" measurements collected in-flight
- Advancements in data acquisition/processing capabilities are providing access to streaming full-flight engine measurement data
- Enables continuous real-time monitoring of engine health, and integration with control logic

Challenge:

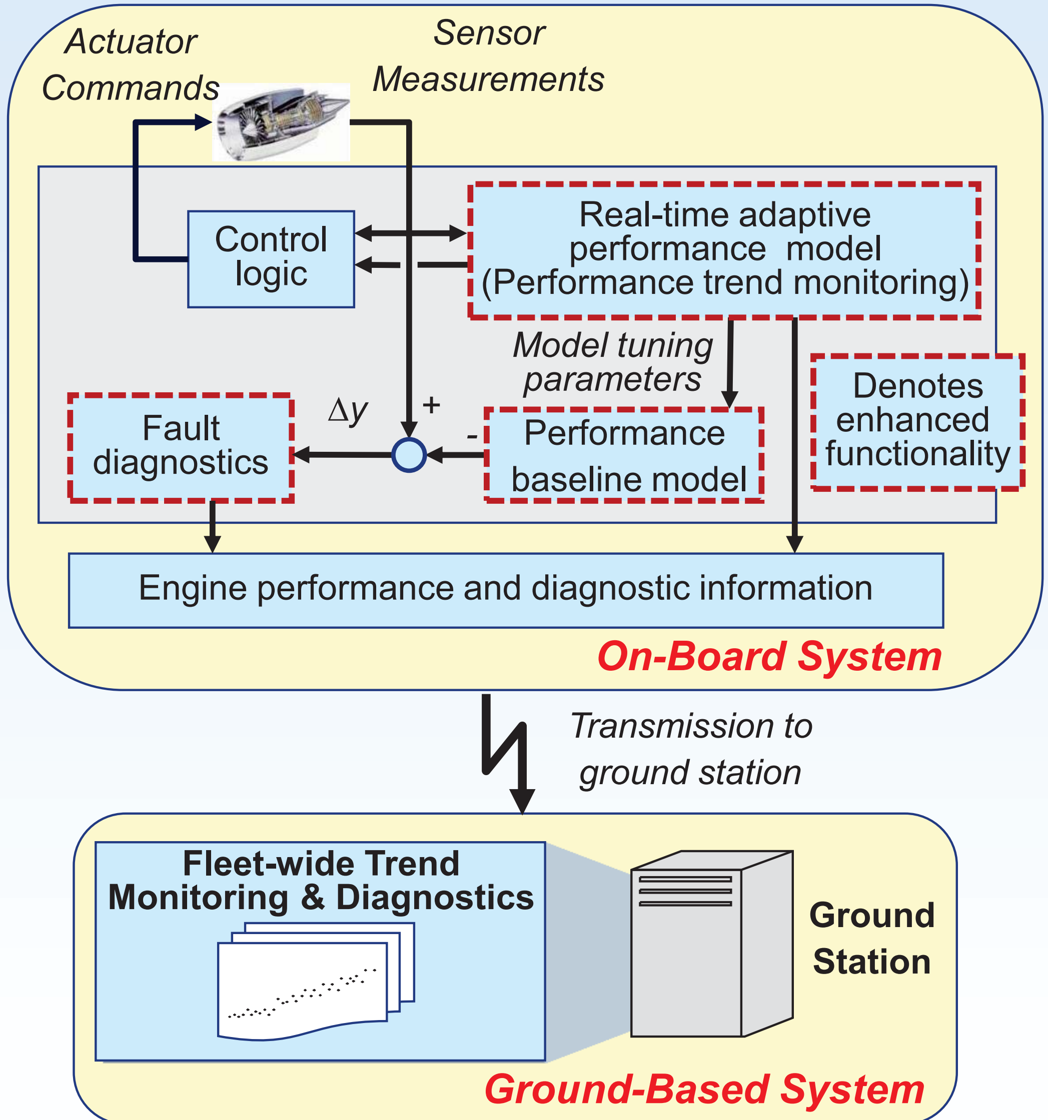
- Streaming data analysis capabilities
- Efficient data compression and data management

Approach:

- Developed an integrated performance trend monitoring and fault diagnostic architecture containing two engine models operating in parallel
  - Real-time adaptive performance model
  - Performance baseline model
- Fault diagnostics based on sensed residuals (Δy) between engine and performance baseline model

Benefits:

- Significant reduction in diagnostic latency
- Ability to diagnoses intermittent faults
- Enabling for model-based controls strategies



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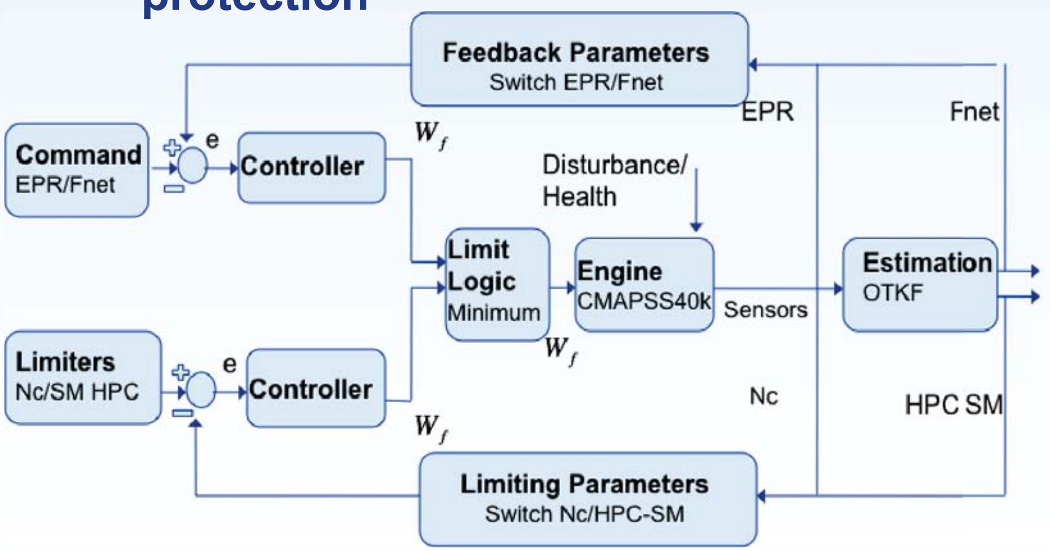
Model Based Engine Control

Goals

- Use an on-board "self-tuning" model of the engine to provide accurate estimates of unmeasured parameters for control design as the engine ages
- Allow for the engine to operate more efficiently and extend operating life

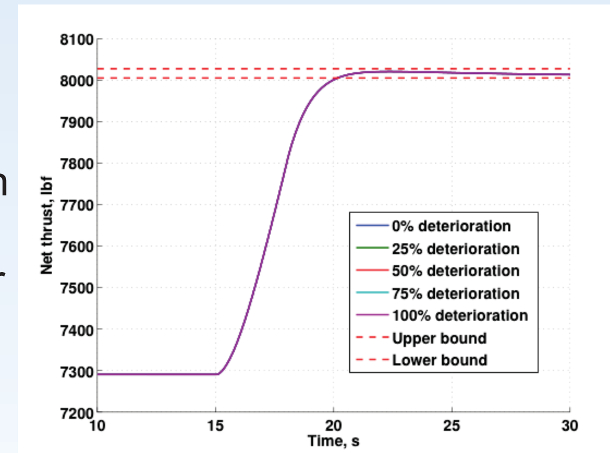
Approach

- CMAPSS40k simulation as baseline engine
- Integrate engine with Optimal Tuner Kalman Filter to get estimates of unmeasured parameters
- Replace current control architecture with a Thrust controller and Stall Margin limit protection

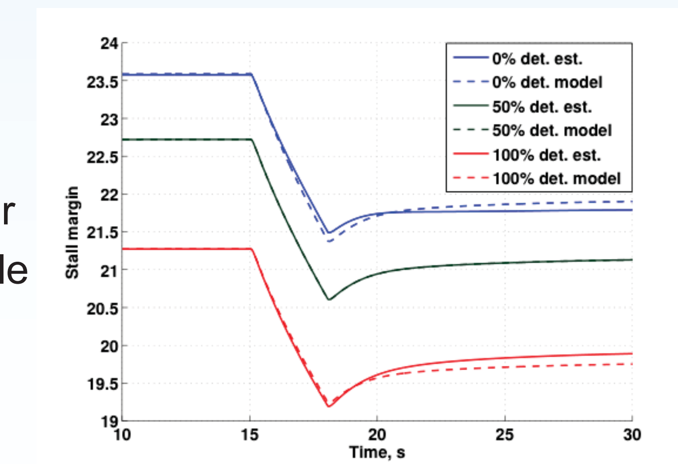


Results

Thrust Control response over engine life with traditional controller error bound



Stall Margin estimation over engine life cycle



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Vehicle Integrated Propulsion Research (VIPR)

Ground-test Maturation of Engine Health Management (EHM) Technology

Background:

- NASA, in partnership with the U.S. Air Force and Pratt & Whitney, is conducting a series of on-ground aircraft engine health management (EHM) technology tests
- This series of tests is collectively referred to as Vehicle Integrated Propulsion Research (VIPR)

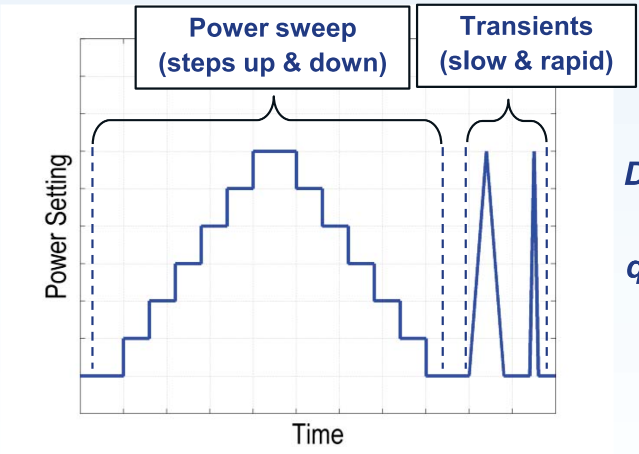
Boeing C-17 Globemaster III Aircraft

Approach:

- A series of on-wing engine ground tests conducted on a C-17 aircraft equipped with Pratt & Whitney F117 high-bypass turbofan engines
- Tests include "nominal" and "faulted" engine operating scenarios

Model-Based Gas Path Health Management Architecture:

- Architecture provides dual-functionality of performance estimation and fault diagnostics
- VIPR testing enables evaluation of self-tuning engine model's ability to track engine performance
- Insertion of gas path system faults (mis-scheduled bleed valves) enables evaluation of gas path fault detection and isolation capabilities



VIPR Event Test Sequence (notional)

Data acquisition over a range of power settings, including quasi-steady-state and transient engine operating scenarios.

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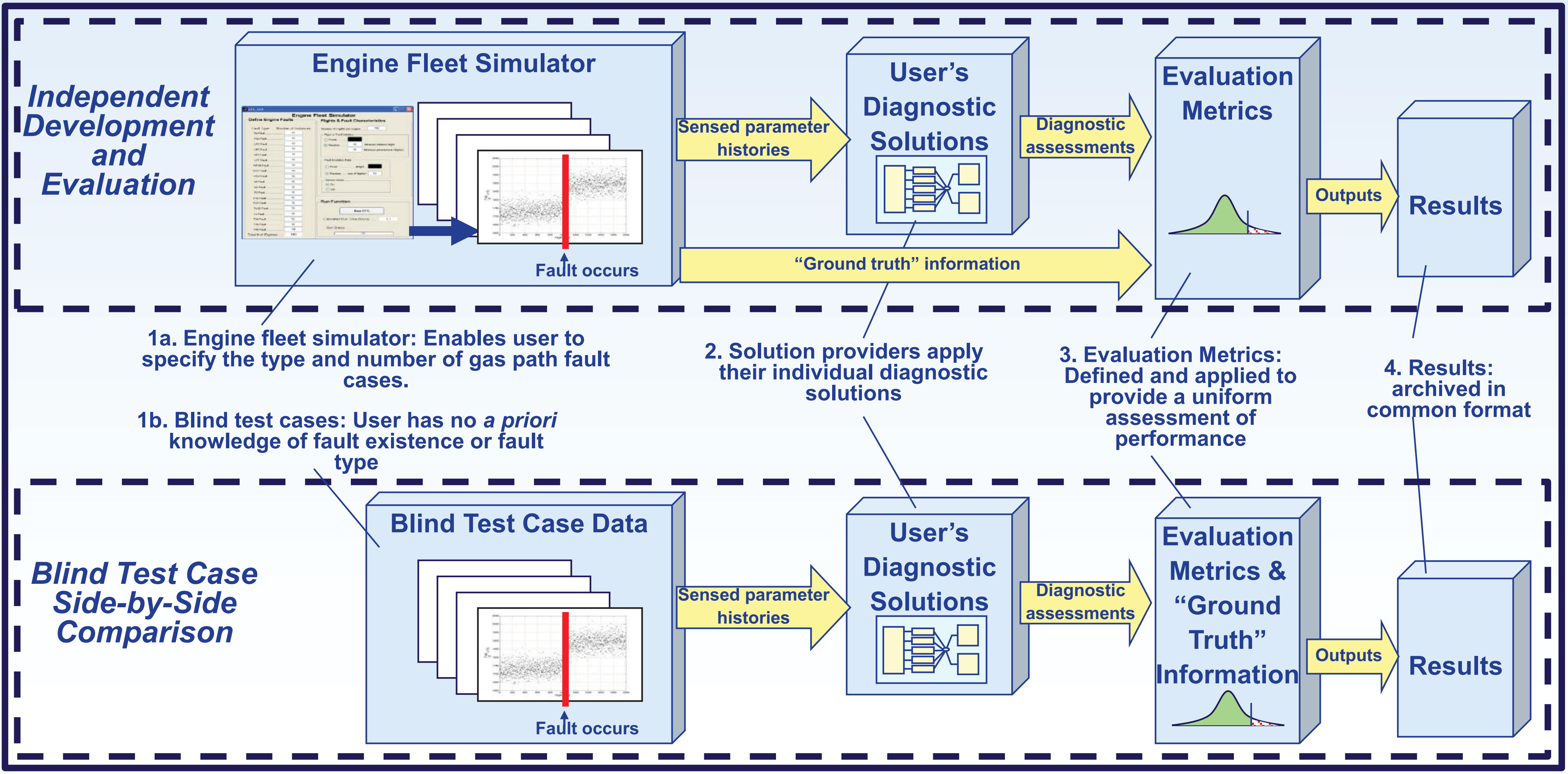
Propulsion Diagnostic Method Evaluation Strategy (ProDiMES)

- *A standard benchmarking problem and evaluation metrics to enable the comparison of candidate aircraft engine gas path diagnostic methods*
- *Simulated problem implemented in the Matlab environment*
- *Publicly available through the NASA GRC Software Repository* *https://technology.grc.nasa.gov/software/*

ProDiMES Public Benchmarking Process

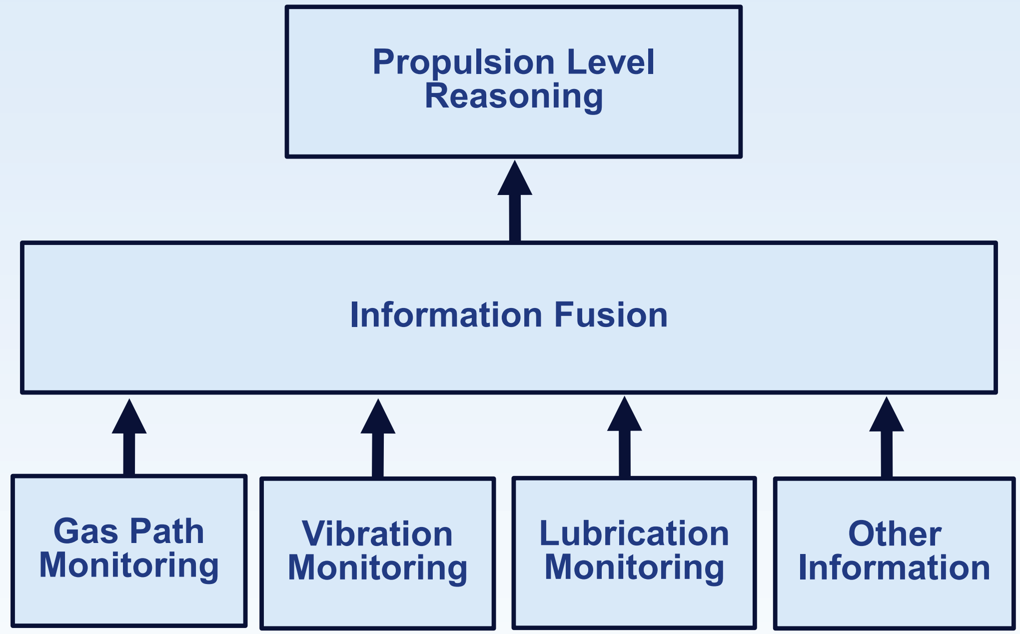


Information Fusion

Leverage all available information

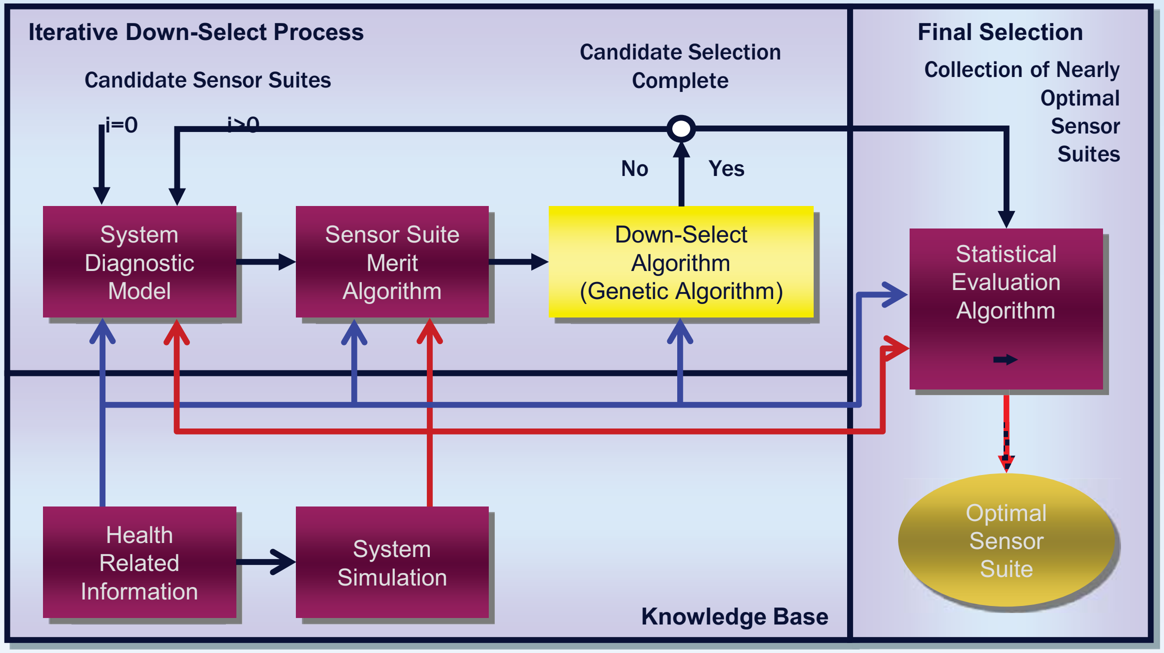
Health inferences do not have to be based solely on gas path measurements!

- Other subsystem health information (e.g., vibration, lubrication, etc.)
- Recent maintenance actions
- Opposite engine health information
- Control information—fault codes, limit activation
- Fleet-wide engine statistics
- Domain expert knowledge / heuristics
- Negative information (the absence of information can be significant)



Information Fusion Architecture

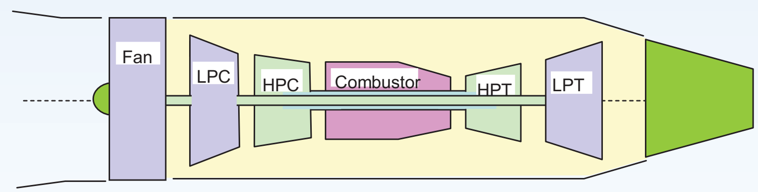
Systematic Sensor Selection Strategy



- The S4 method provides for a systematic way to perform sensor selection.
  - Leverages design and heritage experience base
  - Predicated on the system fault detection/isolation philosophy.
  - Ability to perform sensor selection based on enabling diagnostic approach to discriminate between sensor and component failures.
  - Accommodates various types of models/physical inputs

Propulsion Applications:

- Studies conducted for RS-83 and RS-84
- Selected suites used in RS-84 HM test bed evaluations
- Currently being applied to aircraft engine gas path health monitoring and the Ares Upper Stage J2-X engine



The overall fitness of different sensor suites selected by the S4 algorithm

Target Num	Target Wt.	N1	N2	P2	T2	P1	T1	P3	T3	P4	T4	T5	P6	T6	WF	Fitness	Num Sensors
9	0.000	X	X	X	X			X	X	X	X	X	X	X	X	27.708	12
9	0.010	X	X	X	X			X	X	X	X	X	X	X	X	26.901	12
9	0.100	X	X	X	X			X	X	X	X	X			X	23.161	10
9	0.500	X	X	X	X				X	X	X	X			X	20.857	9
10	0.001	X	X	X	X			X	X	X	X	X	X	X	X	27.653	12

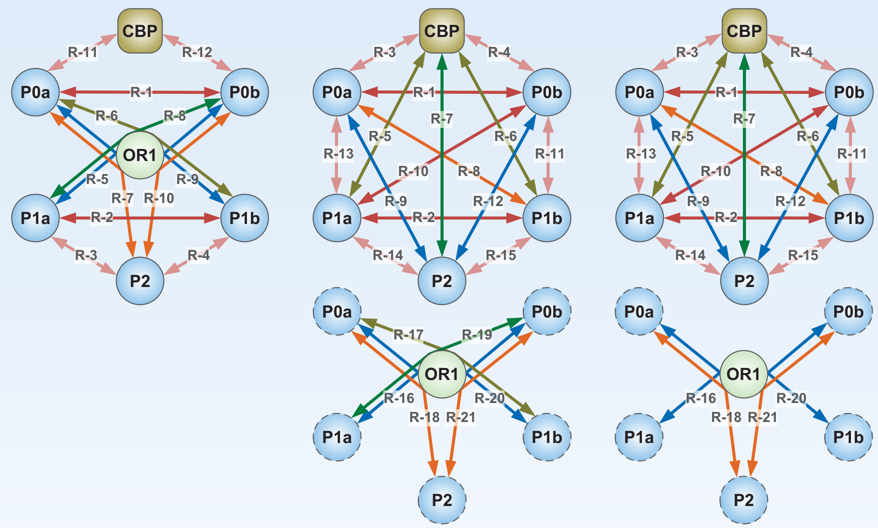
Ares I Real-time Data Qualification Studies
using CDB-developed PHALT & FASTR Platforms

Portable Health ALgorithms Test (PHALT) System ➡

Fuel Actuator System Test Rig (FASTR) ⬇

The 3 Analytical Redundancy Relationship Networks evaluated and summary of results

FASTR-1 FASTR-2 FASTR-3



Test Series	No. Tests	FASTR-1			FASTR-2			FASTR-3		
		Green	Yellow	Red	Green	Yellow	Red	Green	Yellow	Red
1	13	***100%***	***0%***	***0%***	62%	38%	0%	92%	0%	8%
2	4	0%	25%	75%	0%	25%	75%	***100%***	***0%***	***0%***
3	2	***100%***	***0%***	***0%***	***100%***	***0%***	***0%***	***100%***	***0%***	***0%***
4	2	0%	0%	100%	0%	0%	100%	***50%***	***0%***	***50%***
5	8	50%	50%	0%	50%	13%	38%	***75%***	***25%***	***0%***
Combined	29	66%	17%	17%	48%	24%	28%	***86%***	***7%***	***7%***

Green – Correct Detection and Isolation
Yellow – Fault Detected, Incorrect Isolation
Red – False Alarm or Missed Detection

Other IVHM Related Work

- Oil Debris Monitoring
- HUMS – focused on helicopter engine gear box
- Structural Health Monitoring